Enabling Technology for Lunar Surface Science

P. E. Clark, P. S. Millar, B. Beaman, M. Choi, L. Cooper, S. Feng, R. King, L. Leshin, R. Lewis, P. S. Yeh and E. Young

NASA/GSFC, Code 695
Greenbelt, MD
301-286-7457; pamela.e.clark@nasa.gov

J. Lorenz

Northrop Grumman
NASA/GSFC, Code 562
Greenbelt, MD
301-286-4701; john.e.lorenz@nasa.gov

Abstract. Implementation of Lunar Exploration Initiative goals will require deployment of science packages at sites with the appropriate vantage point for obtaining the desired measurements and remote from potential (human) sources of contamination, thus requiring stand alone operation. Chief instruments/instrument package candidates include those which could provide long-term monitoring of the surface and subsurface environments for fundamental lunar science and crew safety. The major challenge such packages face will be operating during long periods of darkness in extreme cold potentially without the Pu238 based power and thermal systems available to Apollo era packages (ALSEP). The initial attempt to design a 10 instrument environmental monitoring package with a solar/battery based power system led to a package with a unacceptably large mass (500 kg) of which over half was battery mass. We achieved considerable reduction in this mass, first through the introduction of high performance electronics capable of operating at far lower temperature, reducing the initial mass estimate by a factor of 2, and then through the use of innovative thermal balance strategies involving the use of multi-layer thin materials and gravity-assisted heat pipes, reducing the initial mass estimate by a factor of 5. Yet to be implemented are strategies involving the universal incorporation of ULT/ULP (Ultra Low Temperature/Ultra Low Power) digital and analog electronics, distributed or non-conventionally packaged power systems, and state of the art solar power technology. These strategies will be required to meet the far more challenging thermal requirements of operating through a normal 28 day diurnal cycle. Limited battery survival temperature range remains the largest obstacle.

Keywords: Moon, Lunar Surface, Instrumentation, Space Physics, Space Environment, Space Radiation, Atmosphere, Magnetic Field, Plasma, Dust , Geophysics, Interior, Heat Flow, Seismometry, Astrophysics

PACS: 07.87.+v, 89.20.Bb, 94.80.+g, 95.55.Ka, 95.55.Pe, 96.12.Hg, 96.12.Jt, 96.12.Kz, 96.20.Jz, 96.12.Pc, 96.12.St, 96.20.Jz

INTRODUCTION

In order to support the development of lunar outpost architecture that will meet the published goals and objectives of the scientific community (Clark *et al*., 2008a; also see NRC Committee on the Scientific Exploration of the Moon, National Academy of Science, Final Report, http://www.nap.edu/catalog/11954.html), we have been part of several interdisciplinary teams of scientists and engineers that have been formulating the implementation of these goals and evaluating surface operational strategies and their implications for surface science activities. Implementation of these goals will require the deployment of science packages, analogous to the ALSEP (Schultz and Crawford, 2008) (Figure 1), to sites with the appropriate vantage points for obtaining required measurement and remote from potential (human) sources of contamination. Chief instruments/instrument package candidates include those which could provide a) early measurements of the atmosphere, radiation, field, charged particle,

CP1103, *Space, Propulsion & Energy Sciences International Forum—SPESIF-2009,* edited by G. A. Robertson

and dust interactions on local and global scales, and b) global scale geophysical network. Such packages must be capable of surviving ultra cold (during extended dark periods) and extreme variations in thermal conditions, as well as operating autonomously with stand-alone power systems whether delivered robotically or by a human crew. From the time of the Apollo era, Pu238 (Plutonium 238) radioisotope based power systems have met the need to supply both power and heat in the coldest and darkest environments like those experienced periodically on the lunar surface, but the availability of radioisotope based power systems over the next decade and a half is now highly uncertain. In fact, our preliminary study demonstrated that when conventional approaches are used in designing instrument packages, performance suffers and mass and cost parameters grow significantly as a result of increased thermal protection and battery power requirements necessary to withstand lunar environmental conditions within needed operational constraints. The efforts described in detail here demonstrate that when alternative state-of-the-art design and components are used, science packages deployed at the lunar poles can meet or reduce the power and mass constraints of Apollo era packages without requiring the use of Pu238.

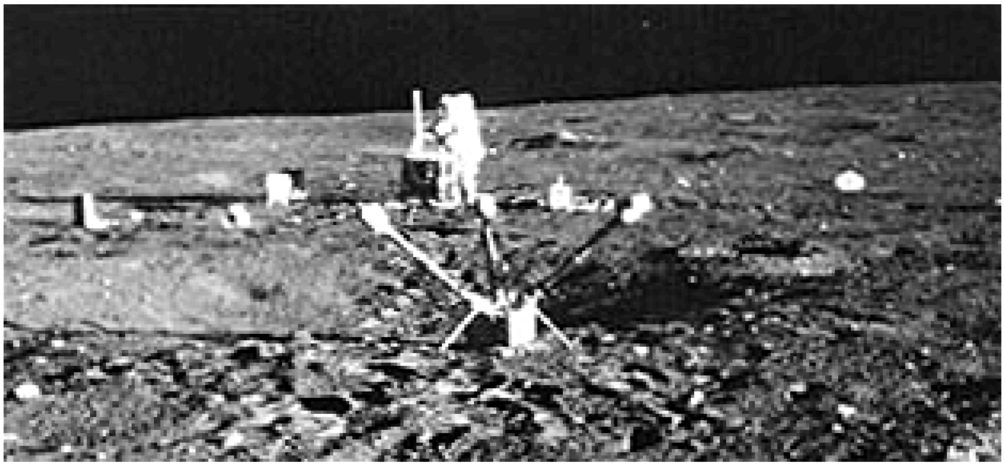

FIGURE 1. The Apollo Lunar Science Experiment Package (ALSEP) deployed on the lunar surface. Note Magnetometer in foreground and astronaut by the CC&DH package behind it.

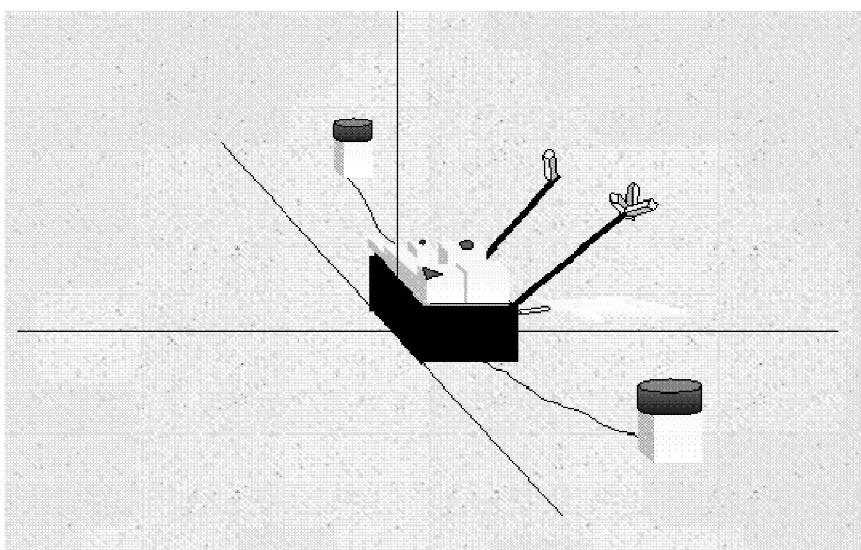

FIGURE 2. Concept of LEMS (lunar environmental monitoring station), analogous to ALSEP, deployed on lunar surface

INSTRUMENT PACKAGES CONSIDERED

Three packages underwent preliminary system and subsystem design using a conventional instrument package design approach at the GSFC IDL (Instrument Development Laboratory) facility. We will describe the highest scientific priority one here, a lunar environmental monitoring station (LEMS) (Figures 2 and 3). Following this, we participated in the system/subsystem instrument integration sessions for two different LSSO (Lunar Suitcase Science Opportunities) packages, which we will discuss briefly here, and for the LEMS using non-conventional design approaches.

LEMS Instrument Package

LEMS, a lunar environmental monitoring station, is a stand-alone automated package concept powered by solar panels with batteries with a suite of instrument and instrument capable of providing comprehensive measurements critical to understanding the interactions between radiation, plasma, solar wind, magnetic and electrical fields, exosphere, dust and regolith (Clark *et al.*, 2007, 2008a and 2008b). Some version of LEMS would be a primary candidate for early deployment before contamination of the lunar exosphere. Instruments include spectrometers to measure neutral gas species of the exosphere, X- and Gamma-radiation, energetic neutrons and protons from the solar and galactic radiation environment; particle analyzers to measure the spatial and energetic distribution of electrons and ions; a dust experiment to measure diurnal variations in the size, spatial, and velocity distribution of lunar and micrometeorite dust; and electric and magnetic field instruments to indicate changes resulting from variations in solar activity, and terrestrial magnetic field interactions.

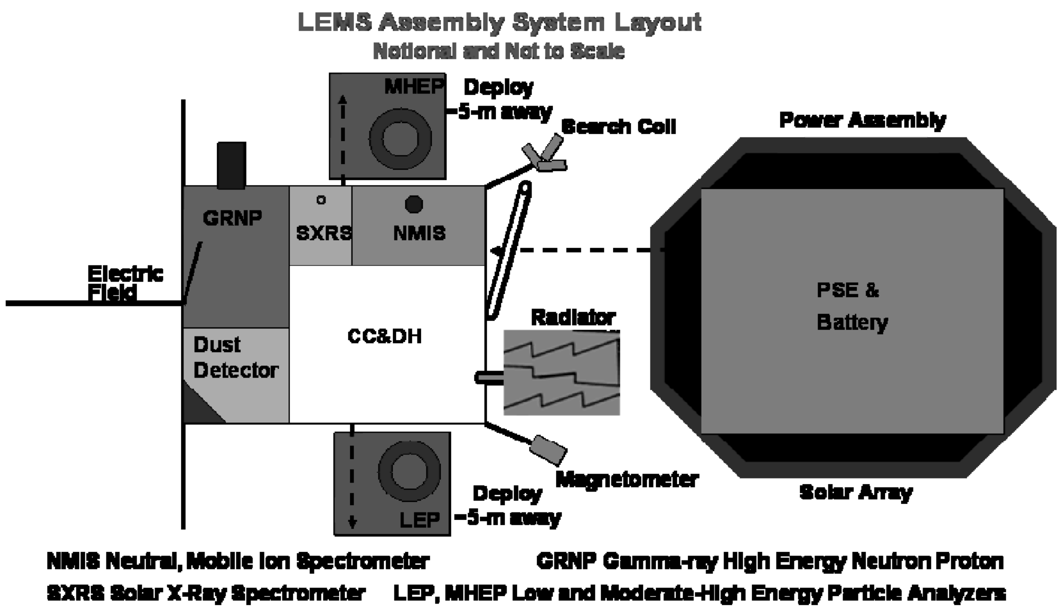

Figure 3. Final Notional layout for the lunar environmental monitoring station (LEMS) - a conceptual deployable science package analogous to ALSEP - including instruments with a wide range of operational requirements, used as an 'extreme' test case for this study. Such a package would provide comprehensive measurements of the lunar environment, a high science priority for early deployment.

LSSO Package

For the last 40 years, several passive retro-reflector arrays deployed by the Apollo astronauts have been used to determine monitor the distance between the Earth and the Moon, providing important information on gravitational physics and dynamics of the Earth-Moon system and on lunar geodesy and the nature of the lunar interior (Faller *et* *al.*, 1969). However, this passive ranging system has limitations that an active transponder system, with its potentially increased precision can address. The LSSO funded precision lunar laser ranging study was designed to develop a concept for a network of suit-cased sized Lunar Laser Transponder (LLT) to be distributed globally on the lunar surface to deliver daily measurements of the Earth-Moon distance at the sub-millimeter level over a period of years. The instrument package consists of a laser transponder with supporting communication, command and data handling systems (Merkowitz *et al.*, 2008).

DESIGN APPROACHES AND METHODOLOGY

Instrument packages in deep space are almost always illuminated by the sun on one side, except for relatively brief periods. Thus, conventional approaches to thermal design for instrument packages rely on the use of heat conducting surfaces to avoid overheating by transferring heat from the illuminated, warm side to the dark, cool side of the package. Design of radiators for such a package, which, whether on a spinning or nadir-pointing platform, is constantly changing its relationship to the sun, is a special challenge. When a package is placed on the surface of a planetary body, where the sun disappears for relatively much longer periods as part of the normal diurnal cycle, the problem is the opposite: surviving the cold. The use of survival heaters would mean the requirement for additional battery power at a time when no solar power is being generated. During periods of illumination, the sun travels in a predictable path which depends on the latitude; thus radiator design will be latitude dependent, e.g., facing directly away from the ground toward space at the poles where the sun is always near the horizon. Here we consider alternative materials, components, and thermal design approaches emphasizing cold survival with minimal use of resources.

Design for Lunar Surface at 'Point of Eternal Light'

The LEMS faces severe challenges even at a 'point of eternal light'. Such a package would be required to be operational for a minimum of five years, to survive the extreme cold (<100K) and thermal cycling during dark periods (up to 5 days even at 'permanently' illuminated polar locations due to lunar librations). Lunar surface conditions are quite different from conventional deep space conditions where one side of the spacecraft is almost always illuminated and heat dissipation is the thermal issue. On the lunar surface, battery mass was driven by the need for power for survival heaters during periods of prolonged darkness and became the overwhelming driver of the total mass to 500 kg (Table I) with only 19% allocated for the instrument payload and 53% for the power system. The power allocation was 180W (85W for the instruments) during the day, 60W for thermal heaters alone at night with the instruments turned off, even though measurements made during periods of darkness are essential (Clark *et al.*, 2007).

As a result of this study, we decided to pursue alternative approaches to thermal and power system design, with the goal of developing instrument packages with mass and power requirements comparable to ALSEP. These approaches are based on incorporation of 1) components that would operate at colder temperatures, while maintaining radiation hardness, such as ultra low temperature electronics (Patterson *et al.*, 2002) strategy for operating instruments during cold, dark periods on a minimal duty cycle to maintain survival temperature; 3) alternative thermal design based on multi-layer insulation over instrument boxes combined with an alternative approach to radiator design incorporating gravity-assisted heat pipes, or thermosiphons (CES, 2008). We also identified components with the greatest thermal survival limitations, such as batteries, and technologies which would enable operation of all components, at ultra low temperature and ultra low power to produce the next generation of instrument packages with masses considerably reduced relative to ALSEP.

Incorporation of High Performance Electronics

Simply introducing more robust electronics capable of operating at colder temperatures, reduced the required battery power required for the LEMS package by a factor of 2, as indicated in Table I. Although not 'standard' for deep space operations at this time, electronics operating at cold temperatures are frequently used in military applications, including polar operations. Ultra Low temperature electronics also have space heritage. Radiation hard cold electronics have also been used in scientific applications, on astronomical spacecraft requiring cryogenic operations for sensor systems, including IRAS (InfraRed Astronomy Satellite), COBE (Cosmic Background Explorer), and ISO (Infrared Space Observatory) (NASA, 2008). We have assumed the universal incorporation of ULT digital and analog electronic components in the instrument package.

Incorporation of Alternative Thermal Design

The use of thermal design and innovative thermal balance strategies are crucial to design a package with mass, power, and volume significantly reduced. This reduction will allow the scientific community to take full advantage of the opportunity for deployment of a wide range of science packages during human crewed missions, and to develop science packages that meet very minimal mass requirements, in the tens of kilograms, for robotic mission payloads.

MLT Packaging Strategy

Our thermal packaging design requires the use of multiple layers of thin (MLT) insulating fiberglass (G10), a material used on JWST (NASA, 2008). Our models indicate that 2 such layers surrounding the 2.5 mm aluminum box which typically encloses and radiation shields instrument components (Figure 4), would be adequate for the package deployed in the environment near the South Pole outpost. To save mass, instruments can be packaged together, except where detection of charged particles and fields requires separation from other sources of interference, and the battery can be packaged to both shield the electronics and be thermally protected by surrounding solar panels.

Radiator Design with Thermosiphons

At any given time during periods of illumination, one or more sides of the instrument package will be receiving full sun. In the polar environment the sun is at or near the horizon illuminating one side of the package, and travels all the way around the instrument (360 degrees) over the course of the diurnal cycle. At the equator, the sun will travel from one side of the instrument to the other, over the top, during the course of 14 days, and then disappear entirely for 14 days. We are designing for the polar environment here, and thus need a radiator surface that faces in the opposite direction from the ground with tray like sides to protect it from solar illumination. It radiates directly 'up' to the 'cold' of deep space without the need for any moving parts. In order to prevent heat loss during periods of darkness, we attach the radiator to the chassis with a thermosiphon (CES, 2008) which will shut down heat transfer by freezing at the condenser end just above the minimum survival temperature: about -40 degrees centigrade. The heat pipe does not require a wick or capillary tube to work as long as the evaporator is below the condenser in the presence of gravity. Because heat pipes require an amount of liquid much smaller than there total internal volume to operate, there is no danger of bursting when the liquid melts. To start up the frozen heat pipe, we run current through small resistors requiring minimal wattage in lieu of strip heaters.

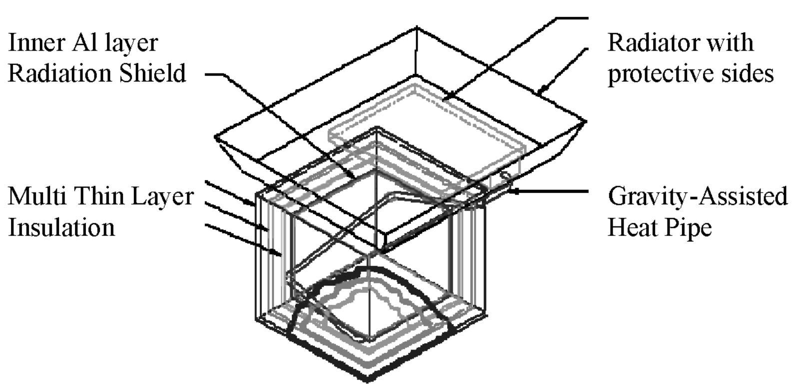

FIGURE 4. Thermal design concept: 1) skyward oriented radiator with no moving parts connected via a 2) gravity-assisted heat pipe capable of freezing at completely by -55 degrees centigrade to the 3) chassis with multi thin layer insulating fiberglass (G10) over an inner 2.5 mm Aluminum box.

RESULTS

The strategies described above combined with operating instruments on 10 to 20% duty cycles, reduce thermal loss, mitigate the need for active survival heaters, and thus reduce the thermal and power system masses. The preliminary results of applying this strategy to the LEMS package shown in Table I indicate that we can reduce the total package mass of the package by a factor of 5 relative to the original mass. Even though we have 9 rather than the 5 instruments typical of ALSEP, we are now operating in the ALSEP regime without the use of Pu238.

Application of Design and Operational strategies

Although have not yet been able to fully incorporate the thermal design strategies into the integration of the LSSO LLT, deployed either at the pole or at lower latitudes, we were able to incorporate cold temperature electronics in most of the design, but with some provisos. The LLT laser as presently designed has a very narrow temperature range for operation and survival. In addition, the low duty cycle (<5%) for instrument operation did not generate enough heat to keep the package above -50 degrees centigrade. Both of these conditions translated into a small active heating requirement during cold, dark periods. After considerable effort, we were able to design a package for deployment at the polar outpost with a total mass of 150 kg. Further mass savings could still be made with application of our thermal packaging concept and tweaking of the laser design.

TABLE I. Table showing reduction in mass and power for LEMS as new concepts were used

Design Regime	Conventional Electronics	Cold Electronics	New Packaging Concept
Operational limit Co	-10	-40	-40
Survival limit Co	-20	-50	-50
Battery Mass kg	240	120	30
Remaining Mass kg	260	260	70
Total Mass kg	500	380	100
Minimum Power W	60	30	10

Identified Enabling Technologies Not yet fully incorporated

Enabling technologies involve electronics and components of the power system. ULT/ULP electronics components, already tested at the chip level (Figure 5), must replace conventional electronics everywhere, from the command and data handling subsystem to the sensor heads. More efficient power system components must be designed to operate in the ULT/ULP regime as well. Promising developments in power supplies and in more efficient, lighter weight solar cells are already underway.

Ultra-low power, ultra-cold operating (ULP/ULT) components

Another strategy that could allow reduced power and temperature operation would be the incorporation of Ultra-low power and low temperature electronics (Maki and Yeh, 2003) developed at GSFC and through partnerships with the University of Idaho and the Department of Defense (DoD) National Reconnaissance Office (NRO). ULT/ULP chips are being used successfully and have demonstrated orders of magnitude savings in power consumption and thermal tolerance. These systems include the use of CULPRiT (CMOS Ultra-low Power Radiation Tolerant) technology successfully flown on NASA's ST5 90 day mission in March 2006.

The Ultra-low power processor scheme would reduce the overall power requirements on the package, which in turn could reduce the size of the solar power and energy storage systems, the need for active heaters and more temperature sensitive electrolytic capacitors. The power requirements for the Ultra-low power processor will not integrate well with traditional power conversion techniques (0.5V output efficiency would be less than 30%), so new distribution schemes and power converter techniques would be needed to accommodate stable reliable power compatible with the Ultra-low power processor (efficiency target of 85%).

Models for CMOS (Complementary Metal Oxide Semiconductor) circuit fabrication components in extremely high or low temperatures are being developed at GSFC, allowing the incorporation of these components in ULT/ULP in a growing number of analog and mixed signal electronics in either FPGAs (Field Programmable Gate Arrays), ASICs (Application Specific Integrated Circuits), or Structured ASICs, combining the advantages of ASICs but at the lower cost of FPGAs, that will perform under the extreme thermal conditions of the lunar surface. We are beginning to incorporate ULT/ULP components extensively in shared or unshared digital electronics of individual instruments, plus communication, control and data handling, power and thermal subsystems.

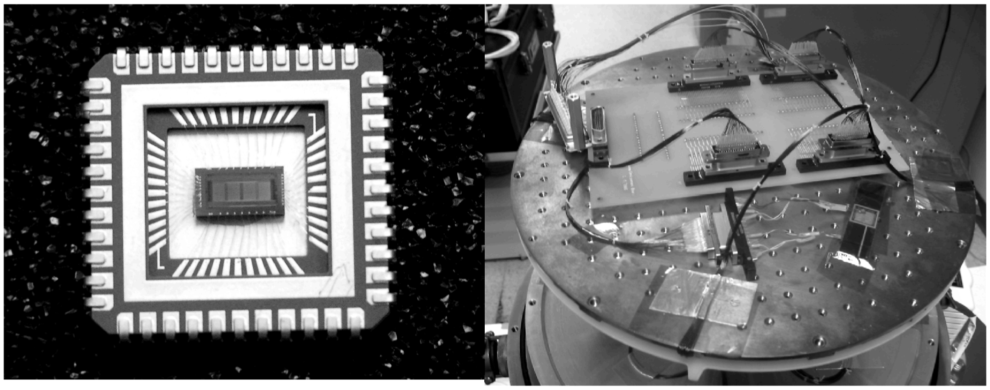

FIGURE 5. Two ULT/ULP design concepts under development at GSFC; on the left, a ULT/ULP Reed Solomon channel coder chip demonstrated on ST5 and on the right, is a bench with ultra low temperature ASICs being tested in the cryogenic chamber.

Battery Concepts

Alternative strategies for the energy storage system have not yet been fully tested and incorporated into our design. We are still in the process of determining how much we can mitigate heat loss by packaging micro-batteries with individual instruments. Alternative battery technology potentially capable of operating at ultra-low temperatures is becoming available for micro-battery applications (West *et al.*, 2000) (Figure 6). These must be considered but may have drawbacks in terms of operating efficiency and mass when built for a small instrument package. The use of a distributed power system will require a much more sophisticated power management system.

Flexible Solar Film

The replacement of solar panels with thin film solar cells, developed under NASA's auspices (NASA Spinoff 2006, "Paper-Thin Plastic Film Soaks Up Sun to Create Solar Energy", http://www.sti.nasa.gov/tto/Spinoff2006/er_4.html), could result in a considerable mass savings because of the inherently higher efficiency of the film and its ability to 'wrap' without structural support (Figure 6). An extremely thin film of amorphous silicon, 40 times more efficient than crystalline silicon used in traditional panels, is vapor deposited on flexible thermally stable support medium. The Nantenna technology which is finally coming of age harnesses mid-Infrared energy to produce electricity even more efficiently (Kotter *et al.*, 2008).

CONCLUSIONS

Overcoming the extreme cold and dark conditions even more demanding than those routinely experienced by spacecraft in deep space, we have successfully have successfully met the challenge of developing a multi-instrument conceptual lunar surface science package deployable at South Pole outpost which has reduced power and mass requirements and improved performance, with capability of gathering data during periods of darkness, relative to the Apollo-era ALSEP. In this way, instrument system and subsystem design, packaging, and integration will significantly enhance the opportunities for the science community to develop selectable, competitive science payloads.

We have also determined that improvements needed to successfully deploy comparable packages in typical diurnal cycle lunar environments will require the incorporation of ultra low temperature and ultra low power components now under development, as well as the development of a managed and distributed power system with much greater capability for surviving at low temperatures.

We are in the process of achieving our ultimate goal of developing a plan for advancing recommended technologies in application to lunar surface instruments, payloads, and associated systems to minimize mass, volume, and power requirements as a precursor to design guideline generation. This approach will leverage NASA's existing and projected unique capabilities within the creation and implementation of these technologies that are critically in demand to serve NASA's Vision for Exploration.

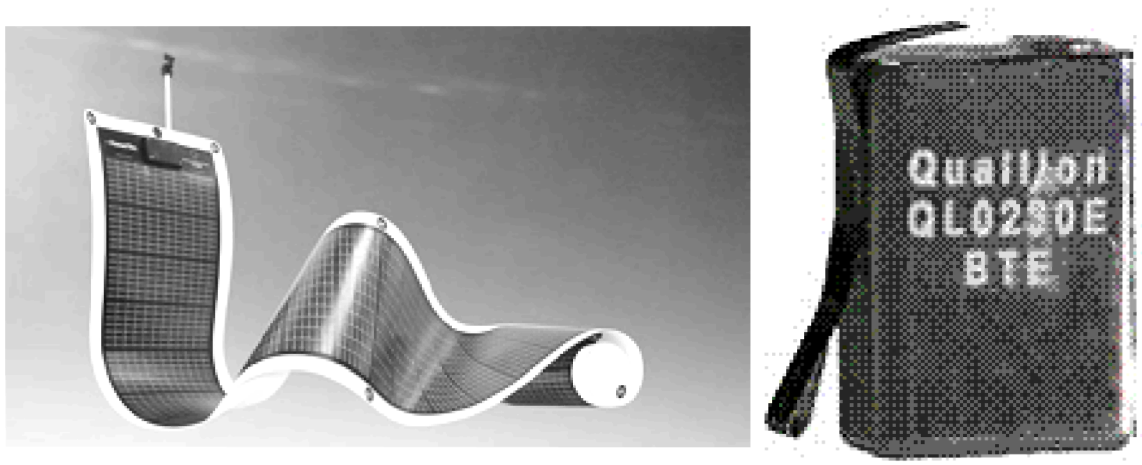

FIGURE 6. Two state-of-the-art concepts for power systems yet to be incorporated into optimized designs for lunar surface science packages, including flexible solar film (left) and micro-batteries to be distributed where heat is being generated during operation.

ACRONYMS

ALSEP	-	Apollo Lunar Science Experiment Package
ASIC	-	Application Specific Integrated Circuit….
CES	-	Commercial Energy Systems
CULPRIT	-	CMOS Ultra-low Power Radiation Tolerant
CMOS	-	Complementary Metal Oxide Semiconductor
FPGA	-	Field Programmable Gate Array
IDL	-	Instrument Development Laboratory
JWST	-	James Webb Space Telescope
LEMS	-	Lunar Environmental Monitoring Station
LSSO	-	Lunar Suite Science Opportunity
LLT	-	Lunar Laser Transponder
MLT		Multi Layer Thin
NRC	-	National Research Council
ULT	-	Ultra Low Temperature
ULP	-	Ultra Low Power

ACKNOWLEDGMENTS

We would like to acknowledge the important discussion pertaining to this work we have had with our colleagues involved with development of radiation, fields, and particle instruments, including Jack Trombka, Danny Glavin, and Michael Collier, and in the LSSO Lunar Laser Transponder and Radio Observatory for Lunar Suitcase Science instrument development, including Joe Lazio, Robert MacDowall, and Louis DeMaio, Philip Dabney, Stephen Merkowitz and Jeff Livas. We thank the GSFC Instrument Development Laboratory personnel, including Tammy Brown and Martha Chu, for their amazing support.

REFERENCES

Clark, P.E., Lewis, R. and Leshin, L., "Optimizing Instrument Packages for the Lunar Surface," *LEAG Workshop Proceedings,* http://www.lpi.usra.edu/meetings/leag2007/pdf/3033.pdf, (2007).

Clark, P.E., Lewis, R., Millar, P.S., Yeh, P.S., Lorenz, J. and Leshin, L., "Next Generation Lunar Science Experiment Packages," *LPS XXXIX*, 1301.pdf, (2008a).

Clark, P.E., Lewis, R., Millar, P.S., Yeh, P.S., Lorenz, J., Feng, S., Powell, W., Beaman, B., Brown, K. and Leshin, L., "Optimizing science payloads for stand-alone operation on the lunar surface in the next decades," *NASA Lunar Science Conference Proceedings*, 2031.pdf, (2008b).

CES Commercial Energy Systems Library, Thermosiphon Heat Exchangers, http://cipco.apogee.net/ces/library/twhtherm.asp, (2005).

NASA JWST, James Webb Space Telescope, JWST Sunshield, http://www.jwst.nasa.gov/sunshield.html, (2007).

Faller, J., Winer, I., Carrion, W., Johnson, T.S., Spadin, P., Robinson, L., Wampler, E.J. and Wieber, D., "Laser beam directed at the lunar retro-reflector array: observations of the first returns," *Science,* **166**, 3901, October 3, (1969), pp. 99-102.

Kotter, D.K., Novack, S.D., Slafer, W.D. and Pinhero, P., "Solar Nantenna Electromagnetic Collectors", *2nd Internatinal Conference on Energy Sustainability*, INL/CON-08-13925, August, (2008).

Maki, G. and Yeh, P.S., "Radiation Tolerant Ultra Low Power CMOS Microelectronics: Technology Development Status," ESTO Conference, http://esto.nasa.gov/oldsite/conferences/estc2003/papers/A3P4(Yeh).pdf, (2003).

Merkowitz, S.M., Arnold, D., Dabney, P., Livas, J., McGarry, J.F., Neumann, G.A. and Zagwodski, T.W., "Precision lunar laser ranging for lunar and gravitational science," *NASA Lunar Science Conference Proceedings*, 2026.pdf, (2008).

Patterson, R.L, Hammoud, A., DIckman, J.E., Gerber, S., Elbuluk, M. and Overton, E., "Electronics for Deep Space Cryogenic Applications," Proceedings of the 5th European Workshop on Low Temperature Electronics, (2002), pp. 207 - 210.

Schultz, A. and Crawford, D.A., "Lunar Atmosphere Composition Experiment", *NASA Lunar Science Conference Proceedings,* 2118.pdf, (2008).

West, W.C., Whitacre, J.F., Brandon, E.J. and Ratnakumar B.V., "Lithium micro-battery development", Volume **16**, Issue 8, Aug., (2001), pp. 31 – 33.